

# TANAMI: Milliarcsecond Resolution Observations of Extragalactic Gamma-ray Sources

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The TANAMI (Tracking AGN with Austral Milliarcsecond Interferometry) and associated programs provide comprehensive radio monitoring of extragalactic gamma-ray sources south of declination  $-30$  degrees. Joint quasi-simultaneous observations between the Fermi Gamma-ray Space Telescope and ground based observatories allow us to discriminate between competing theoretical blazar emission models. High resolution VLBI observations are the only way to spatially resolve the

sub-parsec level emission regions where the high-energy radiation originates. The gap from radio to gamma-ray energies is spanned with near simultaneous data from the Swift satellite and ground based optical observatories. We present early results from the TANAMI program in the context of this panchromatic suite of observations.

## I. INTRODUCTION

Near simultaneous observations across the electromagnetic spectrum are essential to further our understanding of the physics of active galactic nuclei (AGN). Milliarcsecond resolution Very Long Baseline Interferometry (VLBI) observations make a unique contribution as they are the only way to resolve the regions where the high-energy emission originates. VLBI monitoring of AGN jets is the only way to directly measure their relativistic motion and calculate intrinsic jet parameters. VLBI observations let us probe the conditions under which blazars and non-blazars emit  $\gamma$ -rays.

The TANAMI (**T**racking **A**ctive **G**alactic **N**uclei with **A**ustral **M**illiarcsecond **I**nterferometry) program ([14, 15]) provides parsec scale resolution monitoring of extragalactic gamma-ray sources south of  $-30$  degrees declination at dual frequency (8.4 and 22 GHz) by making VLBI observations with the Australian Long Baseline Array (LBA[21]) and associated telescopes in Australia, Antarctica, Chile and South Africa. Observations are made at intervals of about two months. TANAMI observations are complemented by arcsecond resolution monitoring across the radio spectrum with the Australia Telescope Compact Array (PI: S. Tingay) and single-dish resolution radio monitoring with the Hobart and Ceduna telescopes of the University of Tasmania (PI: J. Lovell).

TANAMI began observations in November 2007 with an initial sample of 43 sources consisting of a radio selected flux-density limited subsample and a  $\gamma$ -ray selected subsample of known and candidate EGRET detections. This initial sample has since been expanded to include new detections by the *Fermi* Large Area Telescope (LAT). Details of the sample and observations are presented in [13]. Here we outline some early results from the TANAMI program.

## II. PKS 1454-354

On September 4th, 2008, a strong  $\gamma$ -ray flare was detected by the Large Area Telescope (LAT) coming from the direction of the flat-spectrum radio quasar PKS 1454-354 ( $z = 1.424$ ). This quasar was a possible counterpart of the unidentified EGRET source 3EG J1500-3509 [6]. The flux rose on a timescale of hours before dropping over the following two days. TANAMI images provided the first high-resolution, high-sensitivity parsec-scale image of the blazar jet for the first LAT AGN paper reporting this detection

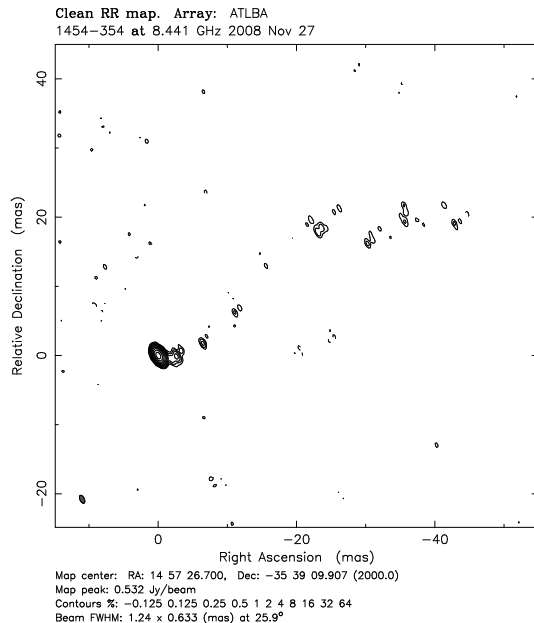


FIG. 1: Naturally weighted TANAMI image of PKS 1454-354 at 8.4 GHz. The image has an rms noise of  $\sim 0.08$  mJy beam $^{-1}$ . The hatched ellipse on the bottom left shows the restoring beam of  $2.87 \times 0.75$  mas at  $4^\circ$ .

and its multi-wavelength follow-up [1].

Figure 1 shows a naturally weighted image of PKS 1454-354 observed at 8.4 GHz on Nov 10th, 2007. The image achieves a resolution of  $2.87 \times 0.75$  mas at an rms noise of  $\sim 0.08$  mJy beam $^{-1}$ . It shows a compact core and a single-sided jet extending to  $\sim 50$  mas at a position angle of  $\sim 300$ , confirming the activity of this source. Model fitting the core with an elliptical Gaussian yields a brightness temperature limit of  $T_B = 1.6 \times 10^{11}$  K. The activity of this source continues to be monitored by TANAMI at unprecedented resolution and dynamic range.

## III. CENTAURUS A

At a distance of 3.4 Mpc [5], Centaurus A is the closest known radio galaxy making it possible to study it at subparsec scales. Not surprisingly, it has been extensively observed at many wavelengths and its basic VLBI-scale radio structure is well-known to consist of a bright jet and a faint counter-jet at a viewing angle of  $50 - 80$  degrees [19].

The TANAMI program has produced one of the highest resolution images of an AGN jet ever made [8]. The uniformly weighted beam with a resolution

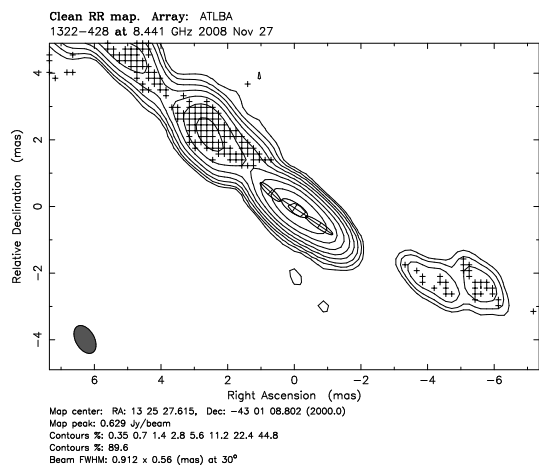


FIG. 2: The core region of Centaurus A at 8.4 GHz. The best view yet of a possible  $\gamma$ -ray birthplace.

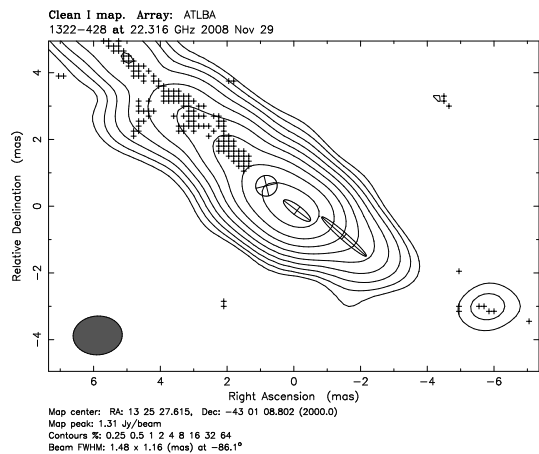


FIG. 3: The core region of Centaurus A at 22 GHz. Note the close agreement with the core region at 8.4 GHz shown in the previous figure.

of  $0.68 \times 0.41$  mas happens to be comparable to the resolution ( $0.8 \times 0.7$  mas) of the previous highest resolution image of this object [7]. Though these observations are separated by about a decade the structures are remarkably similar which would appear to be contrary to the previously reported apparent velocity of  $\sim 1.4$  mas [20]. Velocity information obtained from continuing multi-epoch TANAMI observations is being used to investigate this.

Figure 2 and Figure 3 show the core region from naturally weighted images of Centaurus A at 8.4 GHz and 22 GHz respectively. In both cases the data have been self-calibrated using the CLEAN algorithm and the clean components in the final model have been replaced by Gaussian model components in order to parametrize the core region. There is close agreement between these two figures suggesting that the “core” has the same size at both frequencies. Due to the presence of trans-oceanic baselines to the TIGO

(Chile) and O’Higgins (Antarctica) telescopes only at 8.4 GHz, the lower frequency image has the higher resolution, resolving the core and providing the finest view of the putative  $\gamma$ -ray production region seen so far. These simultaneous dual-frequency data are part of a set of simultaneous broadband data being used to model the behavior of Centaurus A [3].

#### IV. FIRST EPOCH RESULTS

First epoch images at 8.4 GHz of all 43 sources in the initial TANAMI sample have been analyzed and the results are presented in [15]. The images have high dynamic range and are often the best and sometimes the first images of an AGN at milliarcsecond scale resolution. Here we conclude this presentation with a few highlights from this analysis. Unless explicitly stated all discussions below are made with reference to the LAT 3-month list [2].

##### • Morphology and the *Fermi* connection

Figure 4 shows four sources which represent the four morphological classes we have classified the TANAMI sample into. All the images are made with naturally weighted, 8.4 GHz data. The axes are labeled in units of milliarcseconds. The restoring beam of each image is shown as a hatched ellipse on the bottom left and, for the three sources that have known redshifts, a bar indicating a linear scale of 10 pc or 1 pc is shown on the bottom right. The root-mean-square (rms) noise in the images is typically about  $\sim 0.5$  mJy beam $^{-1}$ . The lowest contour level is at 3 times the root-mean-square noise level.

The classification scheme we have adopted is that of [9] which makes no assumptions about the physical nature of the objects thus separating their description from their interpretation. Clockwise from the top left, are examples of single-sided (SS), compact (C), double-sided (DS) and Irregular (Irr) morphology. The initial TANAMI sample has 33 SS sources and 5 DS sources with just one example each of the other two morphological types. Three sources do not have an optical identification. All of the quasars and BL Lacertae objects in the sample have an SS morphology while all 5 DS sources are galaxies. The lone C source is optically unidentified while the only Irr source is a GPS galaxy 1718–649 which is tentatively detected by LAT [4].

In its first three months of operation *Fermi* detected 12 of 43 TANAMI sources with  $> 10\sigma$  significance. All but one of these sources are quasars and BL Lacertae objects with an SS

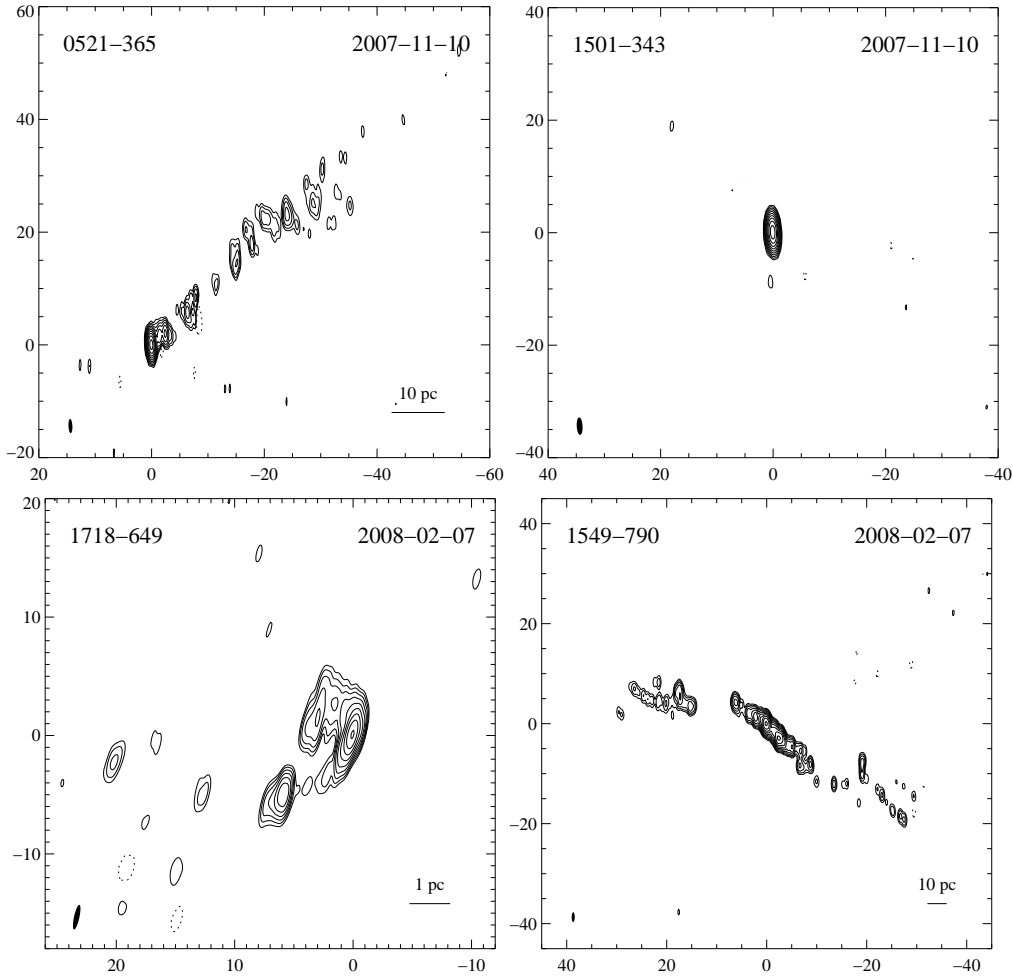


FIG. 4: TANAMI first epoch 8.4 GHz images illustrating the different morphological types in the sample, see text for description. The scale of both axes of each image is in milliarcseconds and the restoring beam is shown as a hatched ellipse on the bottom left.

morphology (the exception is the nearby radio galaxy Centaurus A). This accords well with the canonical view that quasars and BL Lacertae objects have an intrinsically symmetric twin-jet structure that is transformed by differential Doppler boosting to the observed core-jet morphology.

- **Are opening angles correlated with  $\gamma$  luminosity?**

Given the expectation that the  $\gamma$ -ray emission from AGN is beamed and thus orientation dependent, a link between  $\gamma$ -ray emission and the parsec scale morphology of AGN has been sought (e.g. [18]). We fit circular Gaussians to the visibility data and measured the angle at which the innermost jet component appears relative to the position of the core i.e. the opening angle. Of the LAT AGN Bright Sample (LBAS) sources 78% have an opening angle  $> 30$  degrees

while only 27% of non-LBAS sources do. In other words,  $\gamma$ -ray bright jets are pointed closer to the line of sight than  $\gamma$ -ray faint jets. This result should be treated with great caution as the sample size for this analysis is currently small but [16] report similar results.

If confirmed the above result presents two possibilities: either the LBAS jets have smaller Lorentz factors (since the width of the relativistic beaming cone  $\sim 1/\Gamma$ ) or LBAS jets are pointed closer to the line of sight. The former scenario appears unlikely, indeed the opposite effect is reported by [11, 12].

- **Redshift distribution**

The redshift distribution of the quasars and BLLacs in the TANAMI sample is similar to those for the LBAS and EGRET blazars. There does not appear to be any significant difference between the radio- and  $\gamma$ -ray selected subsam-

ples.

### • Brightness Temperature

The core brightness temperature ( $T_B$ ) limit of all initial TANAMI sources was calculated. The high end of the distribution of calculated brightness temperatures is dominated by quasars and the low end by BLLacertae objects and galaxies. Of the 43 sources in the sample, 13 have a maximum  $T_B$  below the equipartition value of  $10^{11}$  K [17], 29 below the inverse Compton limit of  $10^{12}$  K [10], putting about a third of the values above this limit. Doppler boosting is the most likely reason behind these high values though a variety of exotic mechanisms are also possible. There is no significant difference in the brightness temperature distribution of LBAS and non-LBAS sources. Many of the highest brightness temperature sources are not detected by LAT yet which is counterintuitive since they are expected to have higher Doppler factors.

### • Luminosities

The core and the total luminosity was calculated for all 38 initial TANAMI sources that had published redshifts, assuming isotropic emission. There is no significant difference in the distribution of luminosities of LBAS and non-LBAS sources. On the other hand, there is a clear relationship between luminosity and optical type with quasars dominating the high luminosity end of the distribution, galaxies dominating the low luminosity end while the BL Lacertae objects fall in between,

None of the five most distant and most luminous sources have been detected by Fermi in its first 3 months of operation. Intriguingly, none of the nine most luminous jets (difference of total and core luminosities) are detected. If this persists it would suggest a completely unexpected anti-correlation between jet luminosity and  $\gamma$ -brightness.

## V. CONCLUSION

The TANAMI program is providing high quality, high resolution radio monitoring for the southern third of the sky. Such data is a crucial member of the suite of multiwavelength observations that is set to revolutionize our understanding of the physics of AGN in the era of *Fermi*.

Data from the TANAMI program is already a part of several individual AGN studies and statistical analysis of the growing sample of TANAMI sources is providing insight into the nature and origin of high energy radiation from AGN. The availability of core and jet component spectra as well as proper motions is going to greatly expand the questions that TANAMI can help answer.

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